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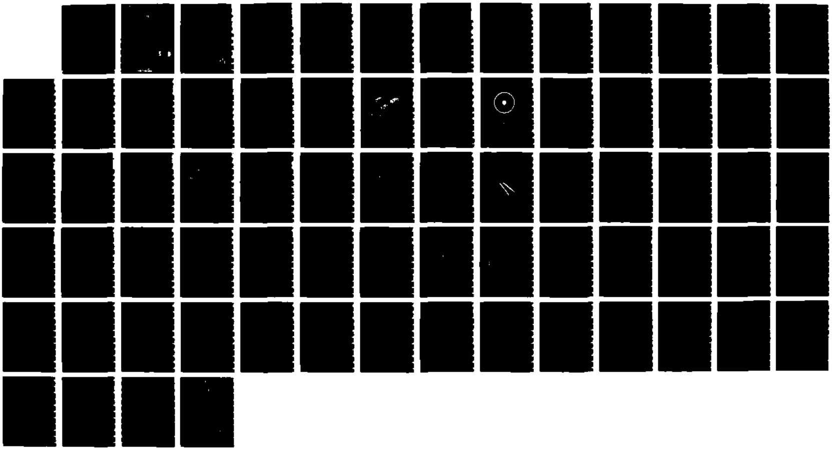

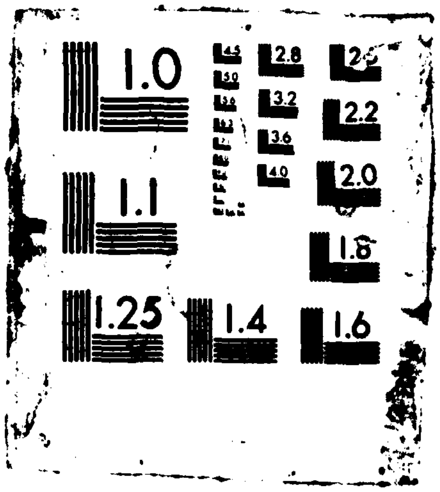
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INVESTIGATION OF ROCKET POWERED, OPEN CYCLE, MAGNETOHYDRODYNAMIC GENERATORS FOR HIGH, PULSED POWER NEEDS IN SPACE

THESIS

John W. Power
Captain, USAF

AFIT/GSO/ENP/86D-1

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Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

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John W. Power, B.S.

Captain, USAF

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John W. Power
Wright-Patterson AFB, OH: 1986

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List of Symbols

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B	magnetic field (tesla)	5
b	Hall parameter	18
c	swirl magnitude (m^2/s)	22
E	electric field (V/m)	5
e	unit charge (coul)	4
I	current (A)	22
J	current density (A/m^2)	5
K	load factor	49
m	mass flow rate (kg/s)	22
n	free electrons per volume (m^{-3})	4
P	power density (W/m^3)	18
v	velocity (m/s)	5
μ	electron mobility (m^2/Vs)	4
μ_0	permeability constant (N/A^2)	47
σ	conductivity (mho/m)	4

Abstract

This investigation examined the possibility of using a rocket powered magnetohydrodynamic (MHD) generator for pulse power in space of 300-megawatts (MW). The result is a preliminary design of an MHD generator using an open cycle disk channel and a single superconducting solenoid coil. The disk channel acts as a thrust deflector, and internal vanes counteract induced vorticity. The use of a solid fuel, wafer grain design rocket motor is proposed for increased electrical conductivity and pulse operation of the generator. Using conservative parameters, a generator design capable of being carried on one or two space shuttle launches is developed with estimated mass of 25,450kg and estimated power output of 1346MW. The nominal operation time before refurbishment is 115 seconds; the restriction on operation time is deterioration of the channel throat. This design exceeds present nuclear and solar cell power systems in power output per unit mass.

I. Introduction

Research Context

There has been considerable speculation recently in the press concerning the type of weapons to be developed from the Strategic Defense Initiative. Some of the ideas, such as directed energy weapons, have a requirement for high, pulse power. These power requirements can be 1000 to 100,000 times the 7.5-kilowatt (kW) solar array used by Skylab (31:498). As an example, there are estimates that missile destroying lasers would have to be at least 100-megawatts (MW) (11:181). Assuming such a high powered laser could meet the 30% beam power-to-input power ratio of the highly efficient carbon dioxide laser (22:140), it would still require over 300MW of input power.

Space power systems are advancing, and NASA has identified more space power as a real need for its future missions (20:810). The U.S. and some European countries are studying the possibility of separate satellites just for power production, but only in the 20-30kW range (10:64). The power required for NASA's proposed space station is 100kW, with later expansion to 300kW (18:80). Solar cell arrays are being considered (25:189), although an array to produce 300kW would be 55 x 55 meters using present technology (18:80). New nuclear systems are being proposed for space, but these are still only in the 300kW region (4:89).

Therefore, current nuclear and solar cell power systems fall short of the power needs for directed energy weapons by a factor of 1000. However, another energy source, known as the rocket powered magnetohydrodynamic (MHD) generator, should be well suited to such high, pulse power needs. In fact, theoretical power outputs using existing rocket engines are from 112 to 9500MW (27:176).

Research Objective

The objective of this research has been to examine the design problems of using a spacecraft rocket engine as a magnetohydrodynamic generator for pulse power systems in space, and to suggest avenues of investigation. The generator was assumed to be in earth orbit and had to supply at least 300MW of power in pulses of at least one second duration.

Although rocket powered MHD generators have the potential to provide pulse power for space systems, there are three major drawbacks. First, the thrust of the rocket engine must be deflected so the space platform does not move. Second, the generator would have to be serviced to replenish the rocket fuel. And third, the magnet system would have to be electrically powered. These drawbacks of thrust deflection, refueling, and magnet power were also taken into account in the design and analysis of the generator.

The research had three major restrictions. The system possibilities were only those using available technology. The MHD generator was restricted to the open cycle type because of the desirability of no moving parts. An open cycle system exhausts the gas instead of recycling it. Finally, mathematical inputs for the generator model were restricted to secondary sources since the researcher had neither the facilities nor the expertise to conduct primary MHD research.

The following chapter gives the basic principles of MHD power generation. These principles are illustrated first with a conventional linear MHD channel and then applied to the disk MHD channel. The third chapter is a review of the current literature including a brief history of MHD research, advances in linear channel design, and advances in disk channel design. Chapter Four gives a qualitative discussion of the three major design considerations: channel, magnet, and fuel. Chapter Five gives estimates of size and mass of the generator as well as usable power output and lifetime. Conclusions and recommendations are given in Chapter Six.

II. MHD Generator Principles

Key Terms

Ionized gas: A gas which has acquired enough energy so that individual atoms or molecules have lost electrons.

Faraday current: Current flow in the working fluid of an MHD generator which is perpendicular to the fluid flow (27:60).

Hall current: Current flow in the working fluid of an MHD generator which is parallel to the fluid flow (1:299).

Conductivity: This is a measure of a material's ability to carry electric current. For a gas, conductivity, σ, is a function of the number density and mobility of the charge carriers (27:23). The free electrons are the primary charge carriers in an ionized gas , and σ in such a gas is defined by (27:24):

$$\sigma = n\mu e \tag{1}$$

where

n = the number of free electrons per unit volume

μ = the mobility of the electrons

e = unit charge

Basic MHD equation: As a conductor moves through a magnetic field, the magnetic field induces an electric

field in the conductor. For an MHD generator, the conductor can be an ionized gas. The electric field, $\underline{E}$, is produced according to the cross product (1:292):

$$\underline{E} = \underline{v} \times \underline{B} \qquad (2)$$

where

$\underline{v}$ = the velocity of the gas

$\underline{B}$ = the strength of the magnetic field

The current density subsequently produced by the induced electric field is directly proportional to the conductivity of the conductor. Assuming the conductivity is a scalar, the induced current density, $\underline{J}$, is given by the following (1:293):

$$\underline{J} = \sigma\underline{E} = \sigma\underline{v} \times \underline{B} \qquad (3)$$

Basic Principles (Linear Channel)

An MHD generator is known as a direct energy converter because it converts thermal directly into electrical energy without a transitional device like a turbine (17:329). Researchers have worked with linear MHD generators, such as the one shown in Fig. 1, for over twenty years (9:2024). The term linear refers to the geometry of the channel itself, and these generators have basic characteristics which are true for all MHD generators.

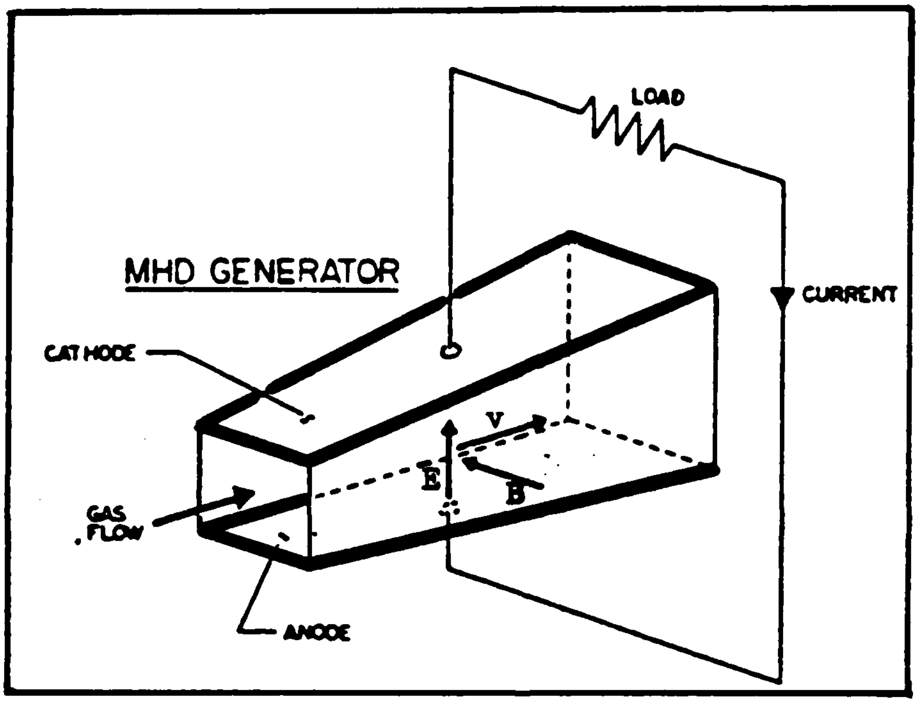

Fig. 1. Diagram of a Magnetohydrodynamic Generator
Reprinted from (9:2028)

The flowing gas, such as the ionized gas of a rocket exhaust, flows through the enclosed pipe or channel. Two opposing walls of the channel are electrical conductors. A magnetic field, vector B in Fig. 1, is produced by external magnets so the field is perpendicular to the flow and parallel to the conducting walls (17:329). Because of the electrical charge of the flowing gas, its movement through the magnetic field produces the electric field, vector E in Fig.1. This field moves free electrons to the anode wall (17:329). The flow of electrons provides the electric current drawn from the generator. (By convention, electrical current is taken to be in the opposite direction from the physical electron flow.)

The power out of an MHD generator is proportional to the velocity of the gas flow times the strength of the magnetic field, which is perpendicular to the flow (27:11). Such a power relationship means a stronger magnetic field will produce more power for the same rate of gas flow. Due to costs and stress limitations, however, the magnets of linear channels are constrained to five to six tesla (17:330).

The gas velocity, of course, could also be increased to produce more power. Increase of the velocity, however, is done by expanding the gas. Expansion decreases temperature and, more importantly, the electrical conductivity of the gas (27:43). Since higher conductivity is

desired, it is an upper bound on the power produced by increasing velocity.

There are energy losses in the MHD channel. These include friction with the wall, heat transfer, electrical resistance of the gas, and electrical losses at the ends of the channel and the conductor walls (17:331). These losses give linear MHD channels using gases at 2000-3000K only a 15% efficiency (35:31).

Hall Effect

The most significant problem with MHD generators is known as the Hall effect. As the electrons flow between the conductor walls, they also produce an electric field along the axis of the gas flow. This secondary electric field moves the free electrons in a direction opposite to the gas flow, thereby reducing the number of electrons flowing between the conducting walls (17:330). To counteract the Hall effect, the conducting walls are segmented in various schemes. Three of these are shown in Fig. 2, diagrams A, B, and C. The shaded areas in the diagrams are the conducting walls. All three of the linear channels shown solve the Hall effect problem, but shape of the magnets to produce uniform fields across the flow can be quite complex (17:330). In addition, the Faraday generator, diagram A, offers a complex loading configuration with individual load circuits for each electrode segment (27:135).

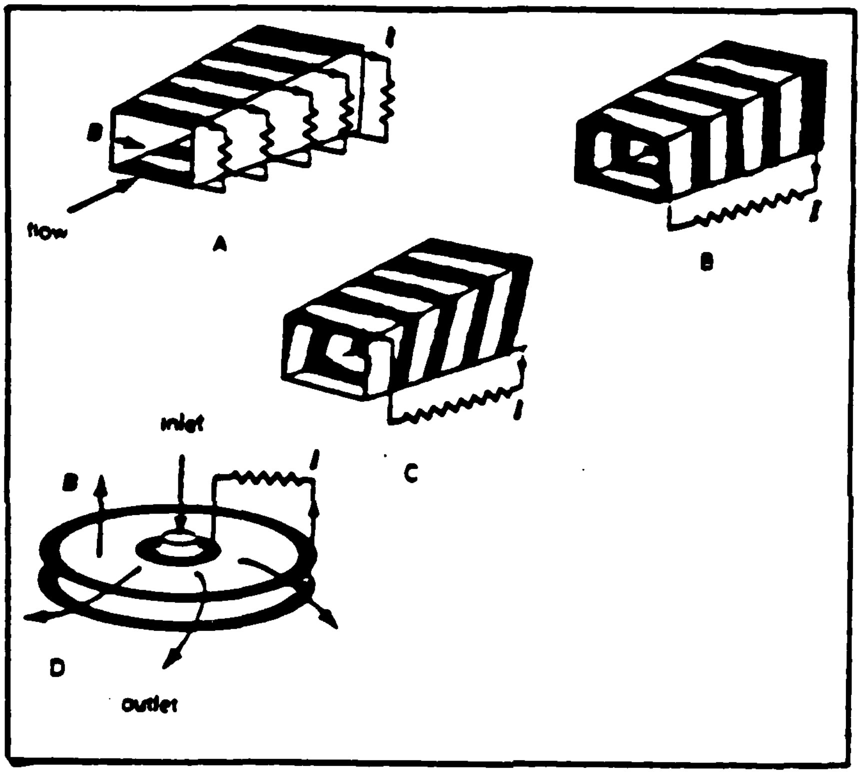

Fig. 2. MHD Linear and Disk Geometries Adapted from (17:330)

Of particular note in Fig. 2 is the Hall generator, diagram B. Instead of eliminating the Hall effect, this generator uses it to draw current in lieu of the opposing electrodes. The opposing electrodes are shorted and their current flow is only there to produce the electromotive force of the Hall effect (27:61). Diagram D shows another Hall generator, the disk generator.

Disk Generator

The disk generator is a unique Hall generator variant. The ionized gas flows into the center and out between the two plates of the disk channel. As with the linear Hall generator, the electron flow from the Hall effect goes opposite to the flow of the gas. There is no need for shorted electrodes, as in the linear case, because the Faraday current flows in concentric circles (J_θ Fig. 3) (26:1506). The gas acts as the "shorted electrodes".

Since the disk generator depends on the Hall effect for its power generation, large magnetic fields with their large Hall coefficients make these generators more effi cient (16:1674). In addition, the greater distance between the electrodes allows the disk generator to support stronger electric fields than the linear channels (16:1676). Now, the extraction of electric energy from the gas thermal energy is proportional to the strength of the electric field. Because disk generators can support three times the electric field strength of the linear generators,

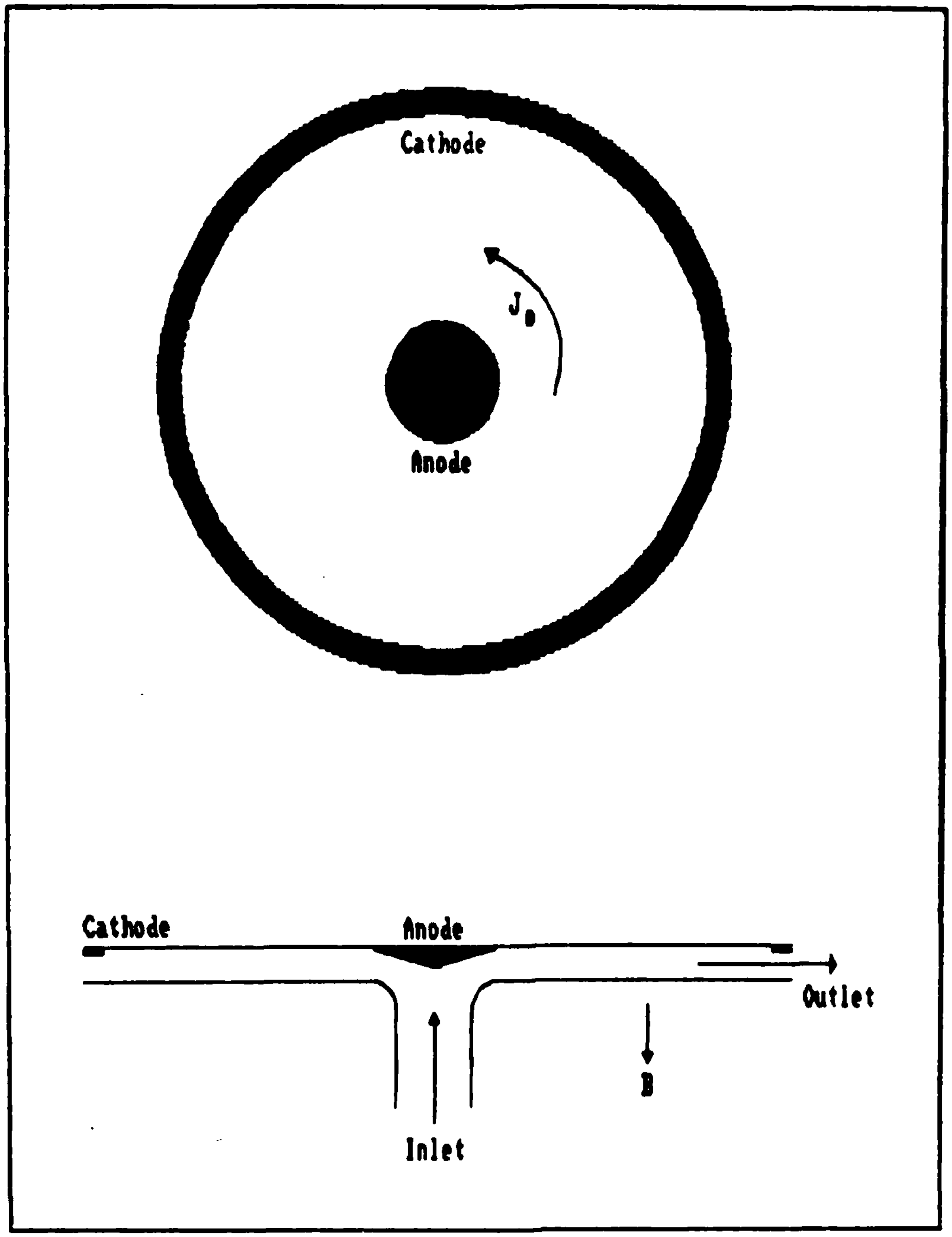

Fig. 3. MHD Disk Generator
Adapted from (26:1506)

they can extract three times the energy for the same channel length (16:1676).

Following the brief history of MHD generator research in the next chapter, an overview of present capabilities of both linear and disk generators is given. Both configurations have advantages and disadvantages.

III. Literature Review

History of MHD Generators

The first patents for MHD generators in the U.S. appeared around 1910, but they were rather vague about operating specifics (27:5). The first sizable generator was built in 1938 in the U.S. but was a failure. The failure was due to not knowing enough about ionized gases and the need for much higher temperatures (17:329).

In 1959, the Avco Everett Research Laboratory successfully made an MHD generator with an output of 11.5kW (27:5). Other experiments followed, including one by the Air Force. Working with the Advanced Research Projects Agency in the early 1960's, the Air Force built an MHD generator powered by an alcohol and oxygen rocket engine. The fuel consumption was 100 lb/sec giving a power output of 32MW, of which 8.2MW was used by the generator's magnets (27:8).

The interest of the Air Force in MHD power generation continued, particularly in the area of portable MHD systems. The component testing of an airborne MHD power source was completed in 1969 (23:1). The generator was a linear channel using a superconducting magnet and intended to power a 250kW plasma arc lamp for target acquisition at night (23:1). The program was terminated before full operational testing could be done (23:145). By 1978,

research was again being conducted to design a lightweight MHD generator, one that would produce 30MW (32:2). The project explored the use of both solid and liquid fuel combustors (shown in Fig. 4 and Fig. 5) with the liquid fuel being JP-4 and liquid oxygen (32:2).

All of the systems mentioned are open cycle systems. Some exploration of closed MHD systems is being conducted but restrictions on closed systems,in addition to the previously mentioned use of more moving parts, make the open cycle more advantageous for space applications. The closed cycle needs a heat exchanger and the available materials limit the maximum peak temperature of the heat cycle (9:2023). Since a higher peak temperature means a higher theoretical efficiency, the US Department of Energy MHD program restricts its development to open cycle systems (9:2023). The DOE program includes both linear and disk geometries for the open channels (26:1506).

Linear Systems

The specific programs mentioned in the previous section were all linear channels. Researchers have the most experience with linear channels. Nevertheless, many of the techniques explored with linear channels have applications to all open cycle MHD generators.

For efficient operation, MHD generators work best at temperatures at or above 2000K (27:8). This is one of

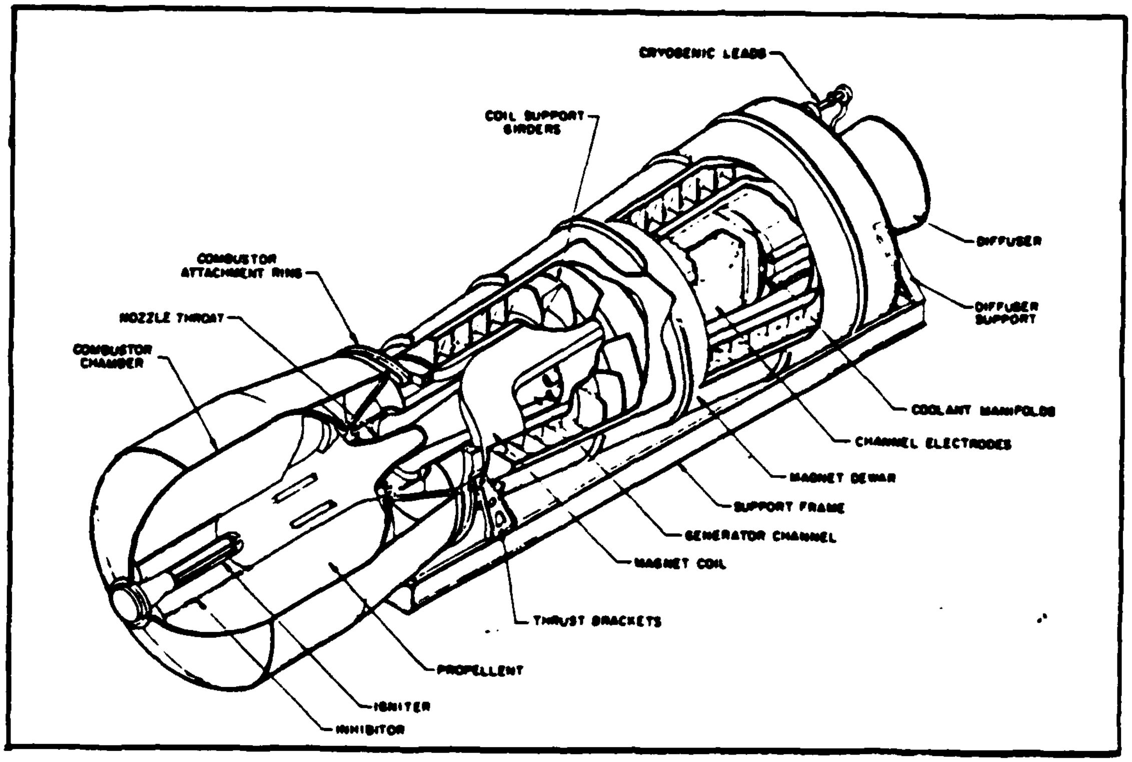

Fig. 4. Solid Fuel Linear MHD Generator
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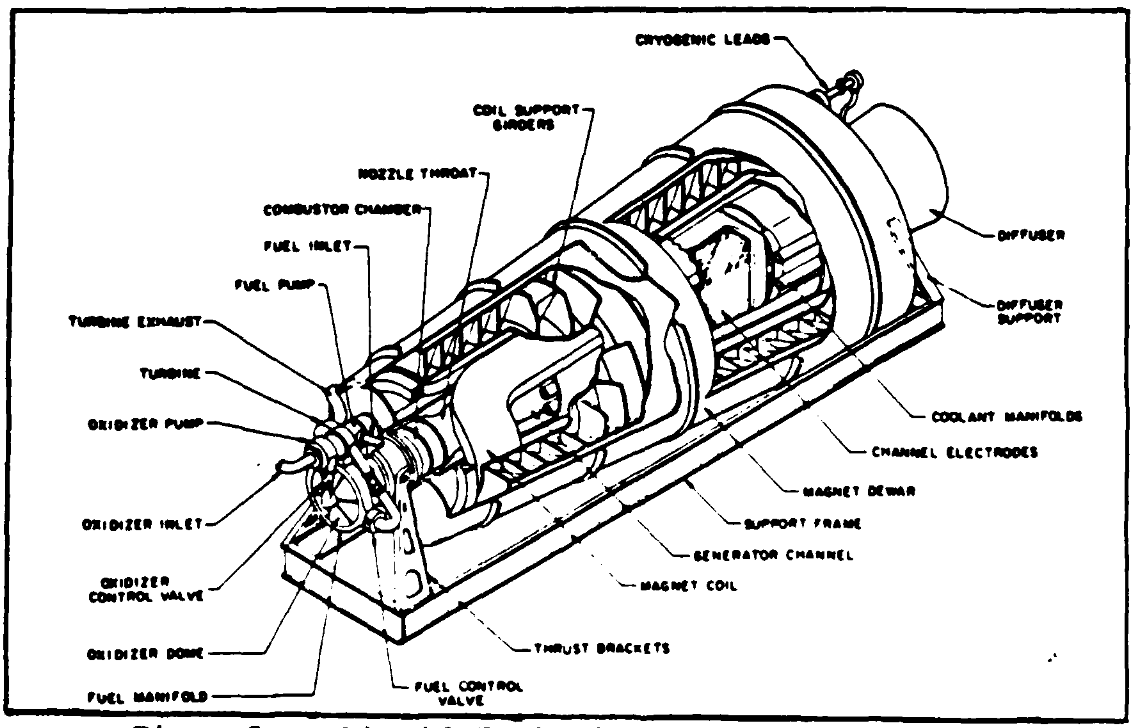

Fig. 5. Liquid Fuel Linear MHD Generator
Reprinted from (29:8)

the reasons rocket engines are good gas sources for MHD because of the high flame temperatures. In fact, a modified version of the Atlas Sustainer Engine could drive an MHD generator with an output range of 150-200MW (29:73).

Channel designs have employed newer and lighter materials. Filament wound fiberglass epoxy has replaced steel for the outer frames of most channels, while ceramics have been used as insulators between electrodes (32:11). Ceramic electrodes are also used in place of copper electrodes. Copper electrodes, without active cooling systems, are limited to runs of about 15 seconds before they melt (6:82). While being able to take more heat, the ceramic electrodes also rise to 90% of full power within 2 seconds, much faster than copper (6:82). Present MHD heat sink designs can operate for 100-150 seconds (36:III-1-16).

One concern of early designers was the effect of waste products, or slag, building up on the electrodes. This was feared to be a problem with MHD generators which were expected to run for great lengths of time. Experiments, however, show that slagging may actually be a protective layer for the electrodes (9:2025). In fact, some designs call for the addition of materials in the fuel to intentionally coat the inside of the channel. Without greatly affecting power output, coating can allow longer channel operation without active cooling (36:III-1-4).

Along with these advances in materials, basic scaling relationships have been found. In experiments with coal fired MHD generators, enthalpy extraction (the conversion of thermal energy to electric energy) went up proportionally with the mass flow rate of the gas (33:145).

In general, enthalpy extraction goes up as the energy input goes up, either by increased temperature or mass flow (34:339). For thermal energy inputs of 2135MW, the enthalpy extraction can be as high as 24.6% (34:343). Also, the efficiency of the generator is proportional to both the length of the channel and the pressure ratio (34:340). The pressure relationship is particularly important for space applications. It means that the performance of an MHD generator should be much better in the vacuum of space than on earth. All of these scaling relationships are a result of MHD power generation being a volume process (29:16). The larger the MHD channel, theoretically, the more efficiently it operates.

As with any device, limitations do exist for the linear MHD generators. Because of the multiple electrode design of most linear channels, the electric fields the channels can support without breakdown are a limiting parameter (34:143). Multiple electrodes are not present or necessary with a disk geometry.

Disk Systems

With stronger electric fields, disk generators can have a higher power density than equivalent linear generators. The maximum power density for a disk generator is at least ten times more than a linear channel by the following relationship:

$$P(d) = b^2 \ P(l) \qquad (4)$$

where

$P(d)$ = power density of disk

b = Hall parameter

$P(l)$ = power density of linear channel

The above relationship assumes equal magnetic fields, conductivity, and volume for both generators (36:III-3-9).

Most linear channels have multiple electrode pairs to overcome the Hall effect and separate loads for each electrode pair to increase efficiency over one single load (38:297). Without the multiple electrodes of a linear channel, a disk generator has fewer parts and connections which means better reliability (26:1508). In addition to reliability, the disk's simpler design can result in 24-56% savings in component costs over linear designs (26:1507).

Current designs for disk generators have the inlet Mach number in the 1.7-1.9 range because studies show disk channels to be more efficient with supersonic gas veloci-

ties (26:1508). With rocket exhaust velocities in the 1500-4000 m/sec range, disk channels appear to be well suited for use with rocket engines (31:41).

Higher gas velocities do impose a penalty. Usually, a higher Mach number means more friction losses along the channel walls (27:43). However, higher Mach numbers also give higher Hall coefficients (27:43). Since the disk is a Hall generator, a higher Hall coefficient means more power extracted.

Experiments with disk channels have been conducted to determine if the theoretical scaling of disk geometries is correct. The experiment (shown in Fig. 6) increased linear dimensions over a previous experiment by a factor of four (13:4). The power extraction efficiency increased by a factor of 1.4 for the large disk over the smaller (13:21).

The advantages of simplicity, compactness, and compatability with supersonic flows made the disk generator a suitable candidate for airborne applications research programs in the 1970's by the Air Force (13:1). Coupled with other advantages outlined in the next chapter, the disk is also the appropriate channel for a space based MHD generator.

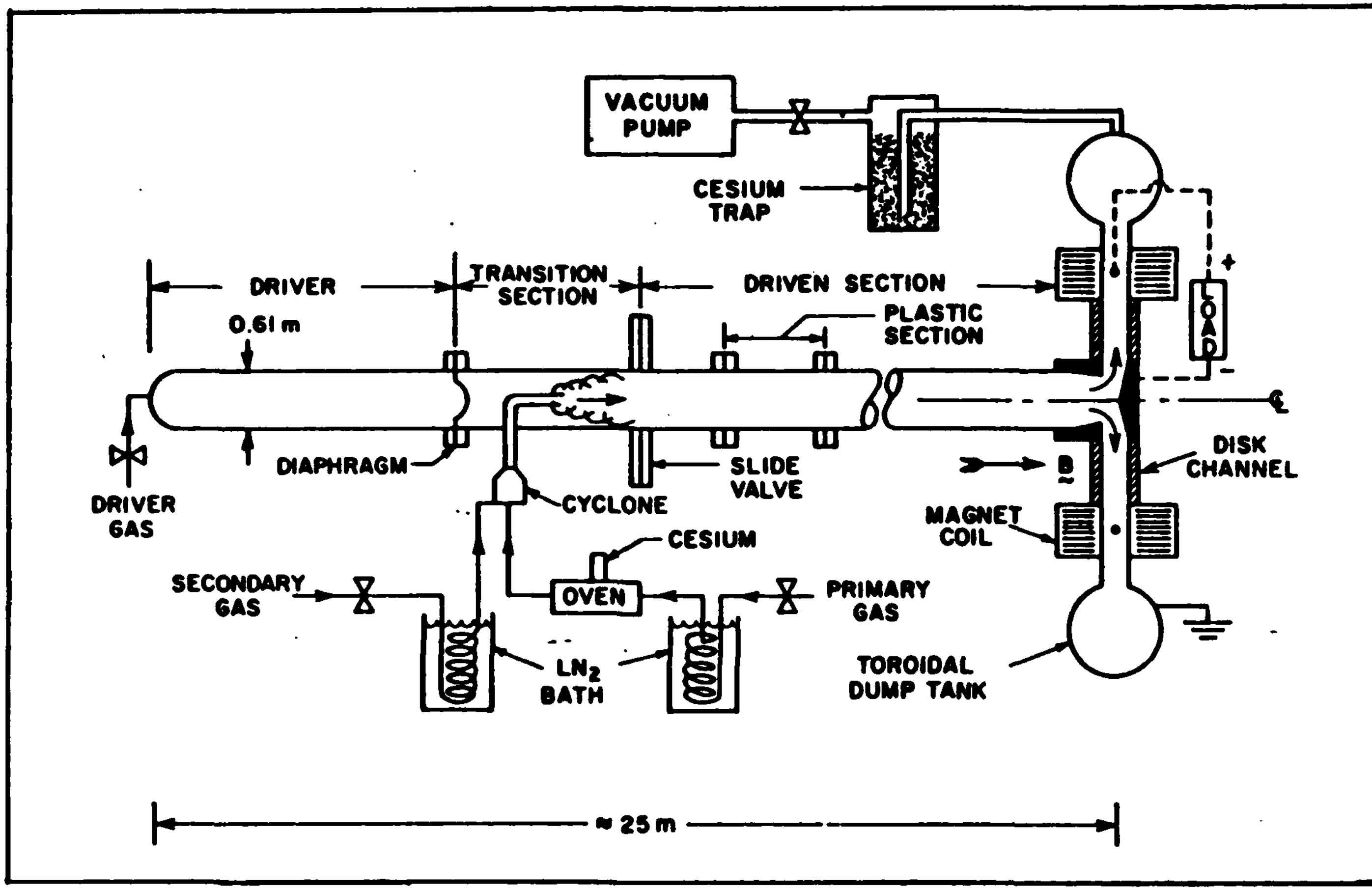

Fig. 6. MHD Disk Generator Experiment
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IV. Generator Design

Choice of Channel

For an open cycle, rocket powered MHD generator in space, the disk channel is superior to the linear channel. Along with the advantages of simplicity and compactness mentioned previously, the disk channel overcomes the chief problem of rocket powered generators in space: thrust deflection. Unlike a linear channel, the disk channel directs the gas flow in a 360° arc which negates any momentum transfer to the generator by the rocket thrust. A linear channel would have to have the extra mass of a separate structure to accomplish the same thing.

The disk generator, however, produces a secondary thrust which would cause the generator to rotate unless also negated. As stated in Chapter II, the Faraday current in a disk generator flows in concentric circles throughout the gas in the channel. There is an electromotive force, known as a Lorentz force, associated with this Faraday current which causes electrons to flow in opposing concentric circles (16:1675). Such a flow, although small compared to the radial flow of the Hall effect, would exert a torque on the generator and cause it to spin in the direction opposite to the electron flow.

This induced vorticity, or swirl, in the gas can be counterbalanced by causing an opposing swirl in the gas as

it enters the disk (16:1675). The velocity component of the gas in the angular direction, v_θ, from any induced swirl and the Lorentz force is given by the following equation (16:1675):

$$v_\theta = c/r - (IB/2m)r \tag{5}$$

where

- c = swirl magnitude
- r = radius of active disk channel (i.e. between anode and cathode)
- I = radial current flow (Hall current)
- B = strength of magnetic field
- m = mass flow of gas through channel

The swirl magnitude is the force exerted by inlet swirl vanes on the gas, times the flow length along the vanes, divided by the mass flow rate of the gas (16:1675). For space applications, the swirl magnitude should be set so that v_θ is zero.

Inducing swirl to counteract the Lorentz force improves efficiency of the disk generator by adding to the radial gas flow (26:1506). The graph in Fig. 7 shows the effect of changes in the ratio of induced swirl to radial velocity on electical efficiency. Induced swirl can improve the isentropic efficiency of a disk channel by as much as 20% (16:1676). Therefore, by indu'ng swirl in the

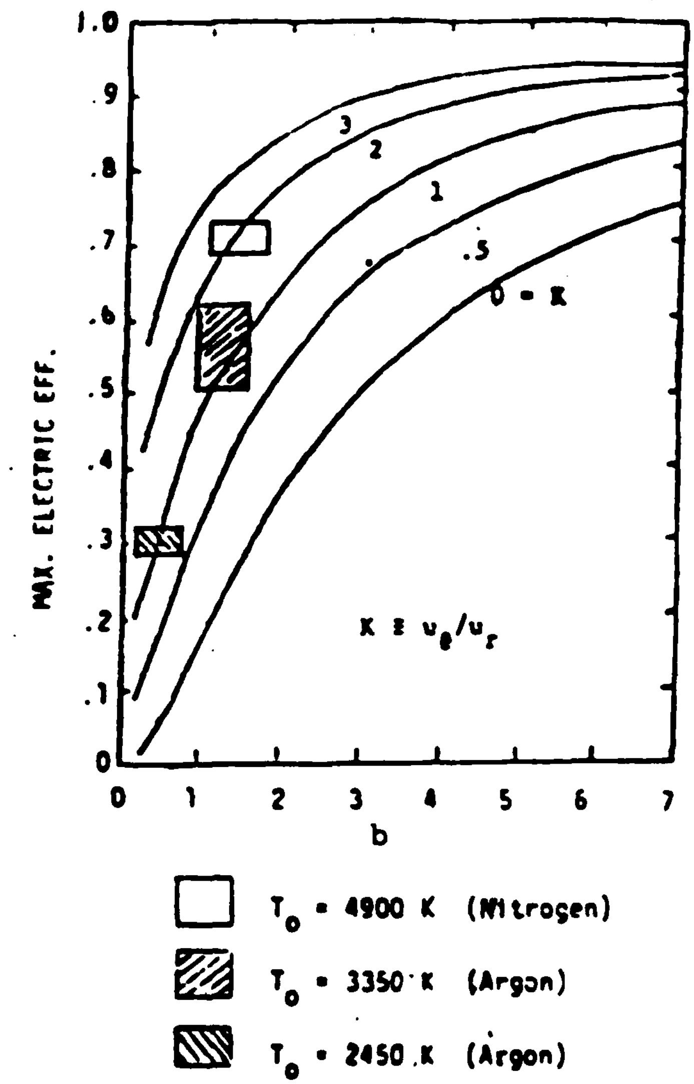

Fig. 7. Swirl Ratio (K) with Electric Efficiency vs Hall Parameter (b)
Reprinted from (36:III-3-7)

gas flow, not only can generator stability be maintained, but the generator's efficiency can also be increased.

Choice of Magnet

Another area where the disk channel simplifies design is the magnet. Instead of the complex saddle coil magnets of linear channels (example in Fig. 8), the disk employs one or two flat solenoids (13:1). The flat coils can tolerate higher magnetic fields, even 7 to 12 tesla, because their simple symmetry avoids the structural problems of the saddle coils (26:1507). The only significant force for a single flat coil is a radial hoop force acting to compress the coil, but copper hoops are quite capable of handling the loads of 5 tesla without additional support (13:30)

Both conventional and superconducting magnets are available for disk generators (9:2024). There are advantages to both types. The cryogenically cooled superconducting magnets use less power but are sensitive to power surges (17:330). Iron core copper magnets need more power to operate but do not need refrigeration and are more tolerant of fluctuations in current (17:330). Magnet system mass, which can comprise 60-70% of the generator dry mass (29:26), is an overwhelming difference between the two types. Comparing a conventional water cooled magnet and a superconducting magnet, the 4 tesla conventional is nearly 5 times more massive than the 5 tesla superconducting

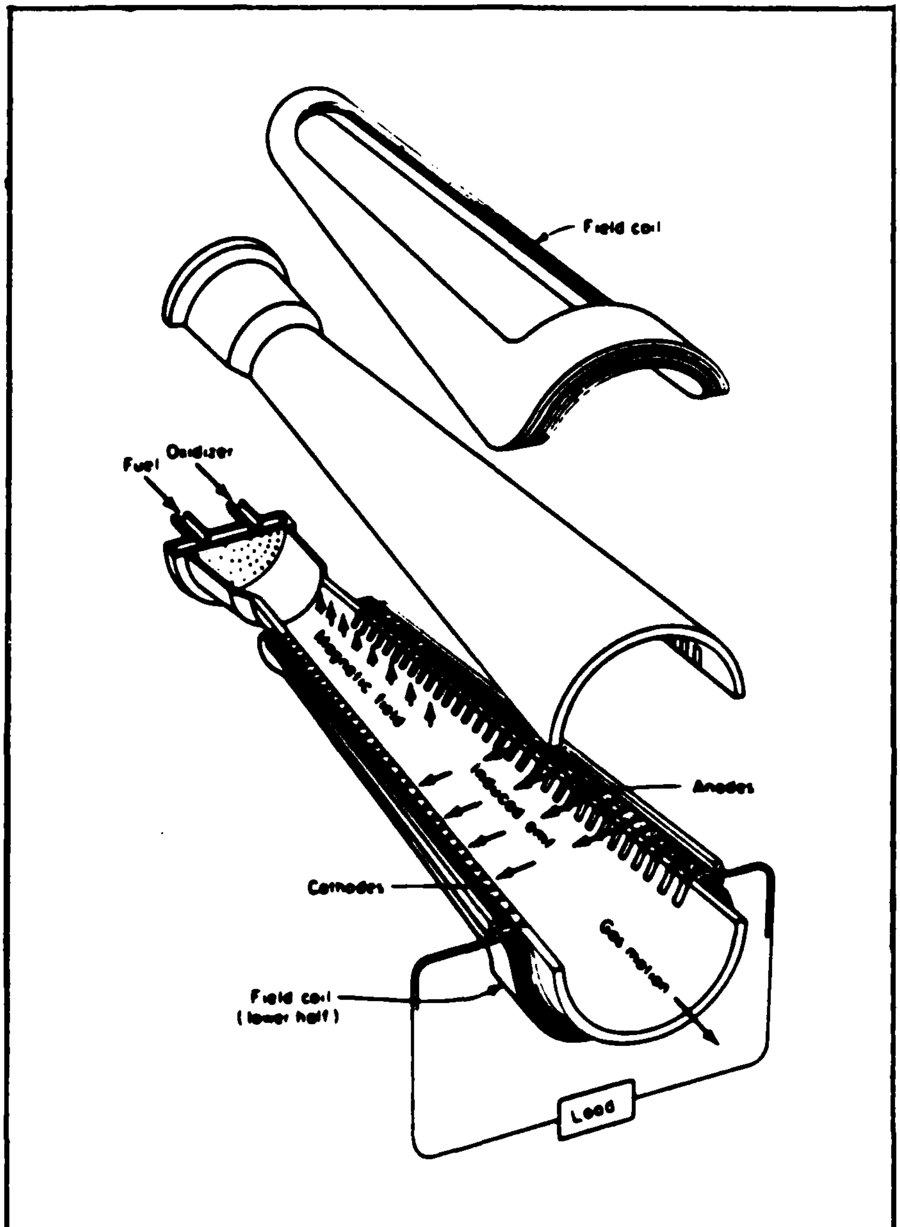

Fig. 8. Linear MHD Generator with Saddle Coil Magnet Reprinted from (27:116)

magnet (19:1479). Such a mass savings is significant in space applications.

It is even possible to use a superconducting magnet without the complexity of mechanical refrigeration equipment. As early as 1967, superconducting magnets in MHD generators were able to be cooled down in a bath of liquid helium and kept below their critical temperature for 12 hours without additional coolant or refrigeration (12:7). Such a system in space could use liquid helium to cool the magnet, with the helium stored in a tank until needed.

Current fluctuations are still a problem with superconducting magnets because of quenching. Quenching is when the temperature of a superconducting magnet becomes high enough that it reverts to a normal conductor (30:14). Local quenching can happen in a small area from small hot spots. The heat put out by the higher resisting normal conductor can cause quenching in the surrounding conductor, thereby spreading the area of normal conductivity. If not cooled, the entire magnet can revert to normal and the magnetic field is elimnated or quenched (30:14). Such quenching can occur when the first pulse of ionized gas enters the MHD channel (12:2). Fluctuations can happen throughout channel operations, usually on the order of milliseconds (14:374). Since quenching can cause anything from taking the power system off line (30:102) to actual magnet damage (30:139), prevention is important. The

choices for control are adequate cooling or an increase in the amount of stable material, usually copper or aluminum, in the magnet conductor (30:102).

Superconducting magnets are made from a combination of a stabilizing metal, such as copper or aluminum, and a superconducting material, such as niobium titanium (NbTi) or niobium tin (Nb_3Sn). Of the stabilizing metals, copper is easier to use but is heavier and more resistant at superconducting temperatures (30:78). Aluminum can decrease the mass of the conductor by a factor of 2.5 (30:80), but is difficult to work with in the pure form required (30:78).

Of the superconducting materials, NbTi is the most widely used and easiest to work with (30:78). Nb_3Sn, on the other hand, can carry 5 times the current density of NbTi (30:81). An increase in current density will reduce the size and mass of conductor needed (30:15). Nb_3Sn can also tolerate temperatures as high as 18K, as opposed to 9.5K for NbTI, before quenching occurs (30:81).

As with aluminum, Nb_3Sn has its drawbacks. It is brittle and difficult to form into wire strands (30:81). Use of a diffusion process to combine Nb_3Sn with a stabilizing metal is possible, but further research on such techniques is needed (29:154). There is a way to use strips of Nb_3Sn combined with stainless steel and copper (shown in Fig. 9) (29:159), but this would not allow the

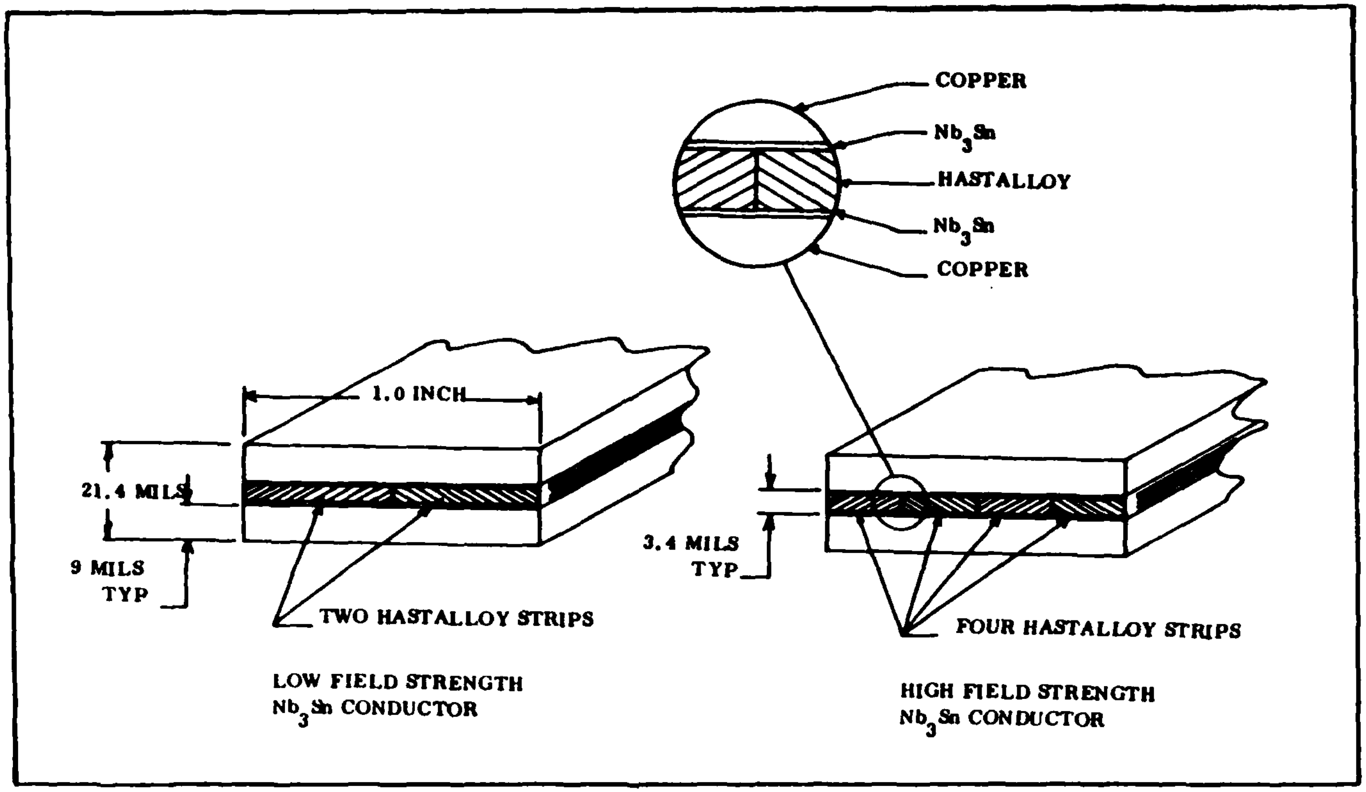

Fig. 9. Niobium Tin Conductor with Strengthening Strips Reprinted from (29:159)

cooling advantages of a braided wire conductor.

Using a braided wire of copper and NbTi has more surface area for cooling purposes than strips (30:72). In one case, the wire was wrapped in a fiberglass-epoxy and then wound into the required magnet shape (30:72). The spaces in the braid were half filled with solder, with the empty spaces left to allow the liquid helium to flow through for cooling (30:72). This extensive conductor surface area helps prevent local hot spots from turning into a quench of the entire magnet.

Superconducting magnets do require some power to operate, although less than conventional magnets. A separate power source is possible, but using power from the MHD generator itself reduces generator mass (36:III-4). A battery would give the initial power to the magnet (shown in Fig. 10), and generator power would be shunted to the magnet until it was at its full operational current density. For large magnets, a charging time of 15 seconds or more can be expected to avoid localized heating from faster charging (30:139).

A disk generator can use either one coil or two coils--one on either side of the channel. The use of two coils gives a uniform magnetic field across the channel but would need internal support struts to keep the coils apart (shown in Fig. 11) which means more mass (26:1509). Therefore, it is best to use one coil and to shape the channel so the gas

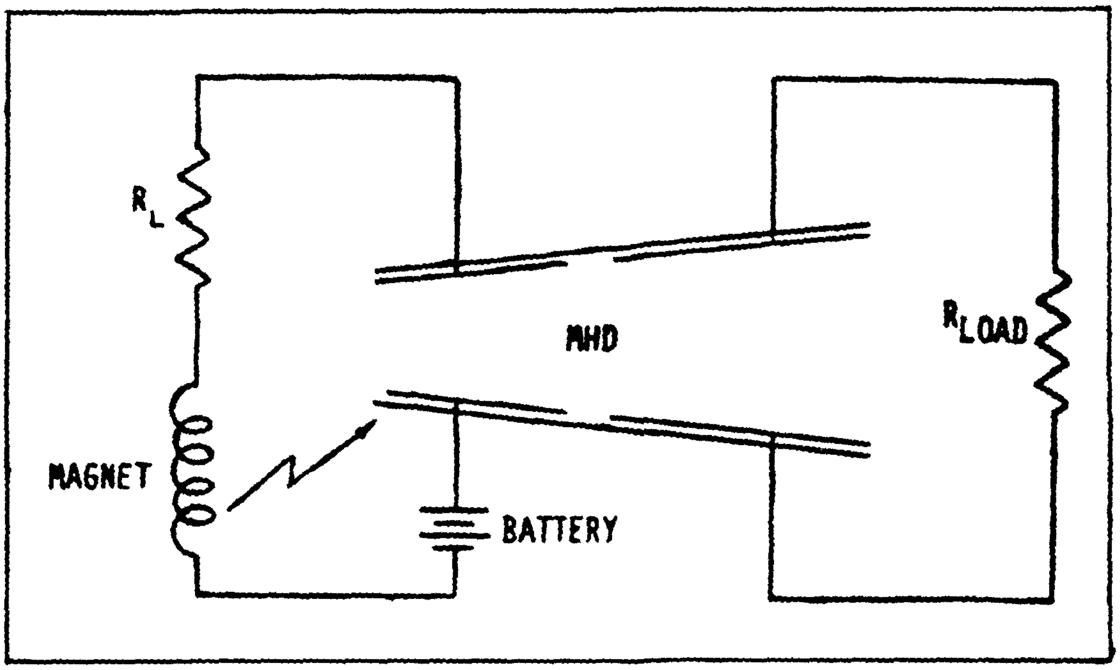

Fig. 10. Simple Circuit for Self-Powered Magnet
Reprinted from (36:III-4-1)

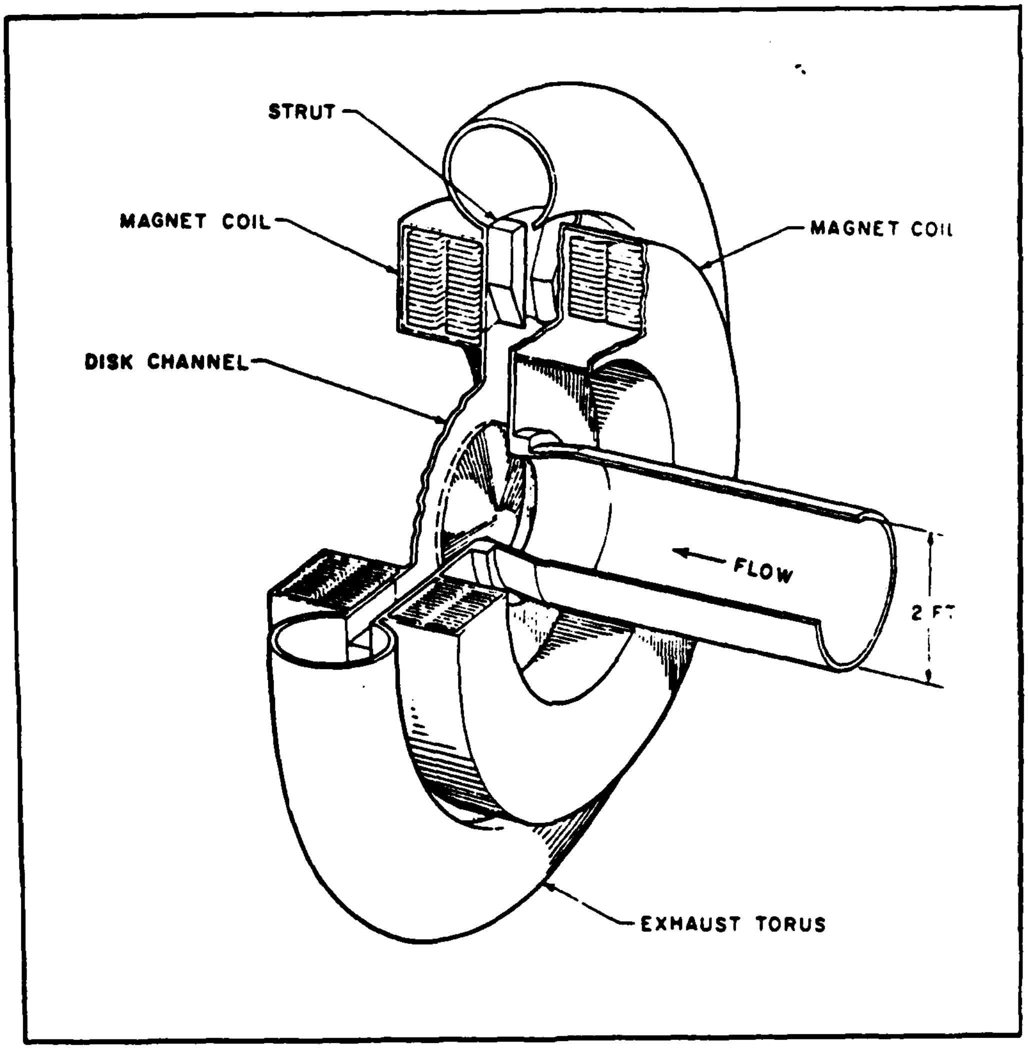

Fig. 11. Two-Coil Disk Generator with Support Struts Reprinted from (13:9)

flow is perpendicular to the magnetic field throughout the channel (26:1509).

The last item to consider for design of an MHD generator magnet is shielding. The magnets used in MHD generators have strong field lines extending far beyond the confines of the channel if they are left unshielded (as in Fig. 12). Although it might not be a great concern for ground systems, the presence of microelectronic systems with the generator in space makes it necessary to shield the magnetic field. There are two methods of shielding, shielding the electronics or shielding the magnet. The shielding of the electronics would be able to work in conjunction with any other shielding, such as defensive shielding, needed for the electronics. For volumes of $1m^3$ or less, such shielding would add less mass to the generator than shielding the magnet (29:192).

Some systems, however, may need to be left exposed to space in order to work, or may be much larger than $1m^3$. In such cases, the magnet itself has to be shielded. Present shielding techniques use a second winding around the magnet conductor. A current is put into the second conductor in the opposite direction of the current flow in the main conductor, the effect being a negation of the stray field lines from the first conductor by the second (29:192). In linear channels, such secondary windings are about half the size of the main conductor (29:195).

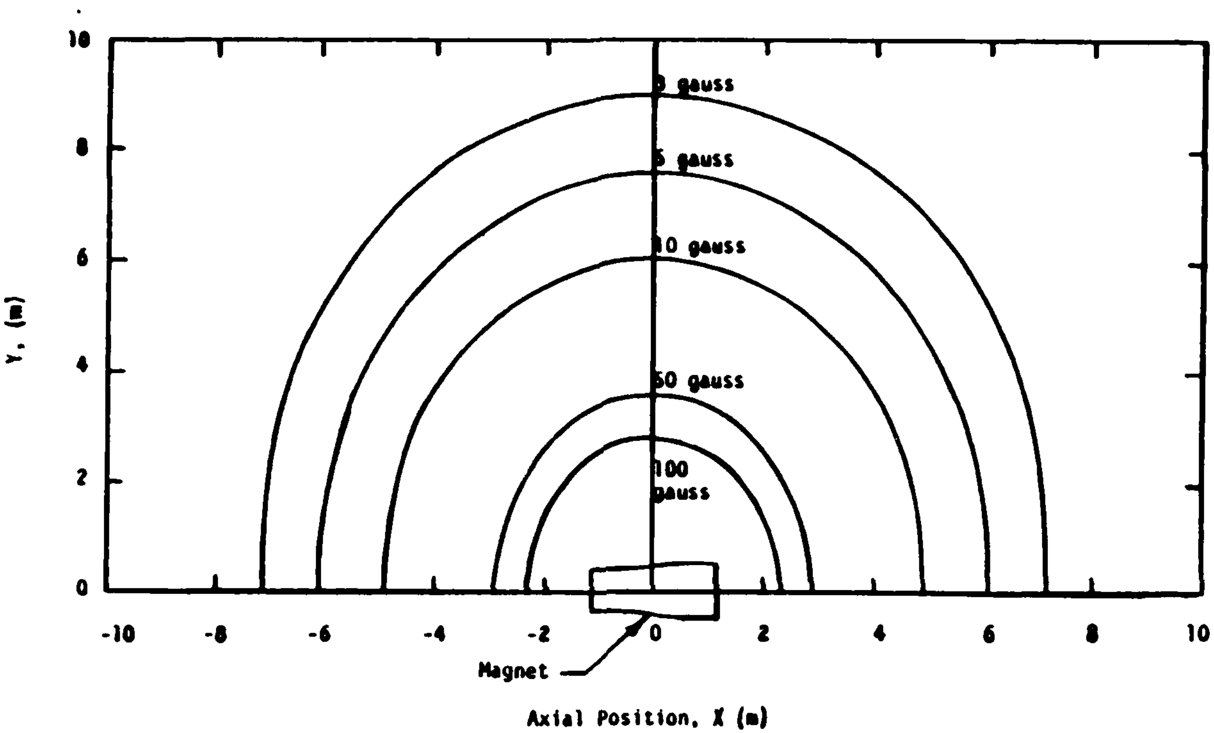

Fig. 12. Stray Magnetic Field from Unshielded Linear MHD Generator Reprinted from (29:191)

It is difficult to tell which type of shielding would be best for a system when the size and requirements of any electronic subsystems using this generator are unknown. A combination of both techniques might be employed. With the certainty that shielding will be needed, this analysis assumes the mass of such shielding to be half the mass of the magnet conductor.

Therefore, the magnet for this generator design is a single coil, superconducting magnet of copper and NbTi. Cooling is accomplished by a bath of liquid helium to ensure conductor temperatures of 4K. The helium is injected into the magnet dewar from a holding tank when the generator is activated. Enough helium is supplied to ensure 12 to 24 hours of magnet operation without mechanical refrigeration. Power to the magnet will be primarily from the generator with initial power from batteries. A reasonable current density for this magnet is 15,000 A/cm^2 (29:165). A field strength of 6 tesla is assumed since at least 4 tesla is necessary for an MHD generator using supersonic flow (19:1477).

Choice of Fuel

For rocket engines, the fuel choice comes down to liquid or solid. Mass, of course, is a prime concern. The mass of fuel and oxidizer is a significant portion of system mass for runtimes of a couple of minutes or more (29:28). It turns out that solid fuel has less mass and

takes up less volume than liquid fuel of equal thermal energy (32:33). Actual fuel mass to power output for liquid and solid fuel in a 25MW MHD generator are 0.083kg/kW and 0.077kg/KW respectively (29:15).

Another advantage of solid over liquid fuel is the lack of moving parts. Liquid engines need pumping systems and pressure regulation. Solid rocket motors need only an ignitor, which can be a simple squib (29:130). The lack of moving parts improves reliability and durability. In addition, solid motors have a faster start time than liquid engines (29:100). Although liquid engines have been able to achieve start times of 2 seconds or less (32:27), solids have consistantly shorter and reliable start times even after 9 years of storage (29:100).

Liquid and solid fuels also have different electrical conductivities for their exhaust gases. Liquid fuels have less conductivity than solids, even though reducing the electron collision cross section of its exhaust can improve the conductivity (36:III-1-4). Addition of cesium to the fuel can also increase the conductivity as much as 20% (29:105). Even with these and other methods, the conductivity for liquid fuels is still in the 13-15 mho/m range (32:23). Such conductivities are adequate for MHD generators, which only require 10 mho/m (8:433).

Solids, however, can far exceed such conductivities. In one MHD experiment, the average conductivity for a solid

rocket motor was from 40-50 mho/m (3:1648). Solids can employ high energy binders in the fuel mixture to increase the flame temperature and thereby increase the conductivity by up to 10% (29:105). Solid fuels can also replace cesium with potassium and reduce fuel costs by a factor of 10 (29:68). In an experiment, a double-base metalized solid fuel with only 5% potassium had a conductivity of 100 mho/m (3:1647).

For reasons of reduced mass and volume, simple and reliable operation, and increased conductivity, solid fuel was chosen for the generator design. Since the generator is intended to be operated in a pulse mode, attention must now be paid to the controllability of a solid rocket motor. There are currently four methods of operating a solid rocket motor in a pulse mode: cartridges, adjustable nozzels, hybrid engines, and wafer grain motors.

The first of these methods is the use of multiple cartridges, one cartridge for each pulse (2:7-2). The cycling of such cartridges for many pulses make it too complex for space applications.

The second method is using an adjustable nozzle throat which would change the throat area (29:115). To cut off the motor, the throat area is increased until the pressure drop in the combustion chamber extinguishes the fuel. Such a method would require moving parts in the high temperature throat area. Expanding the throat can also

cause an erratic extinguishing of the rocket thrust (24:80). Such systems capable of five pulses, however, have been demonstrated (29:115).

The third method is a hybrid rocket design using a liquid oxidizer and solid fuel (example in Fig. 13). One commercial firm has already conducted test firings of such an engine and plans to use it in a launch vehicle (28:1E). Although such a system adds mass and complexity to the solid rocket motor, it does offer a low cost alternative for a small trade-off in engine performance (31:419).

The final method is to use a wafer grain design. Such a solid motor (example in Fig. 14) has layers of solid fuel separated by thin layers of insulating material (29:127). Each layer represents one pulse and has its own ignitor and firing circuit (29:129). The end burning design of the wafer grain also gives a constant chamber pressure and thrust, but exposes the chamber wall to the hot combustion gases (24:63). Some ceramic coatings used on liquid engine combustion chamber walls have lasted for several hours of operation and might be useful in the wafer combustion chamber (36:III-1-5). Because of its lack of moving parts, the wafer grain appears to be the best choice for a controllable solid rocket motor (29:117).

In constructing such a wafer grain motor, the ignitors are sunk into the layers of fuel (29:117). The size of ignitor needed depends on the open volume in the com-

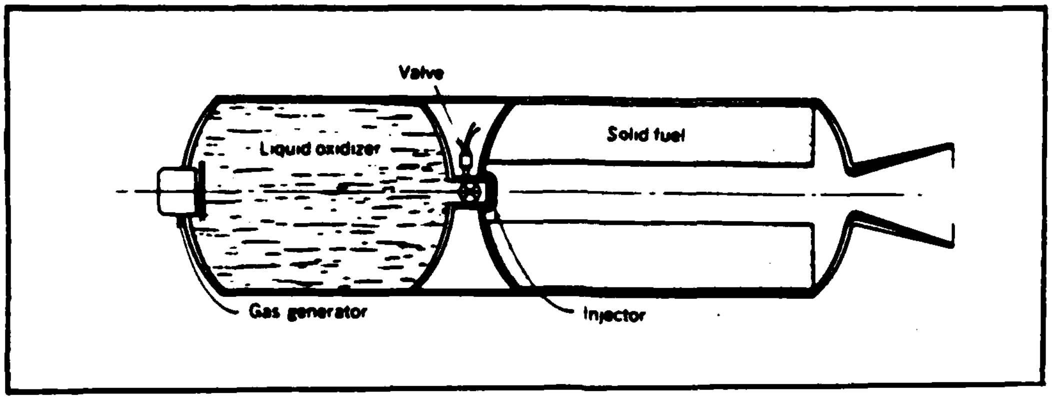

Fig. 13. Diagram of Hybrid Rocket Engine
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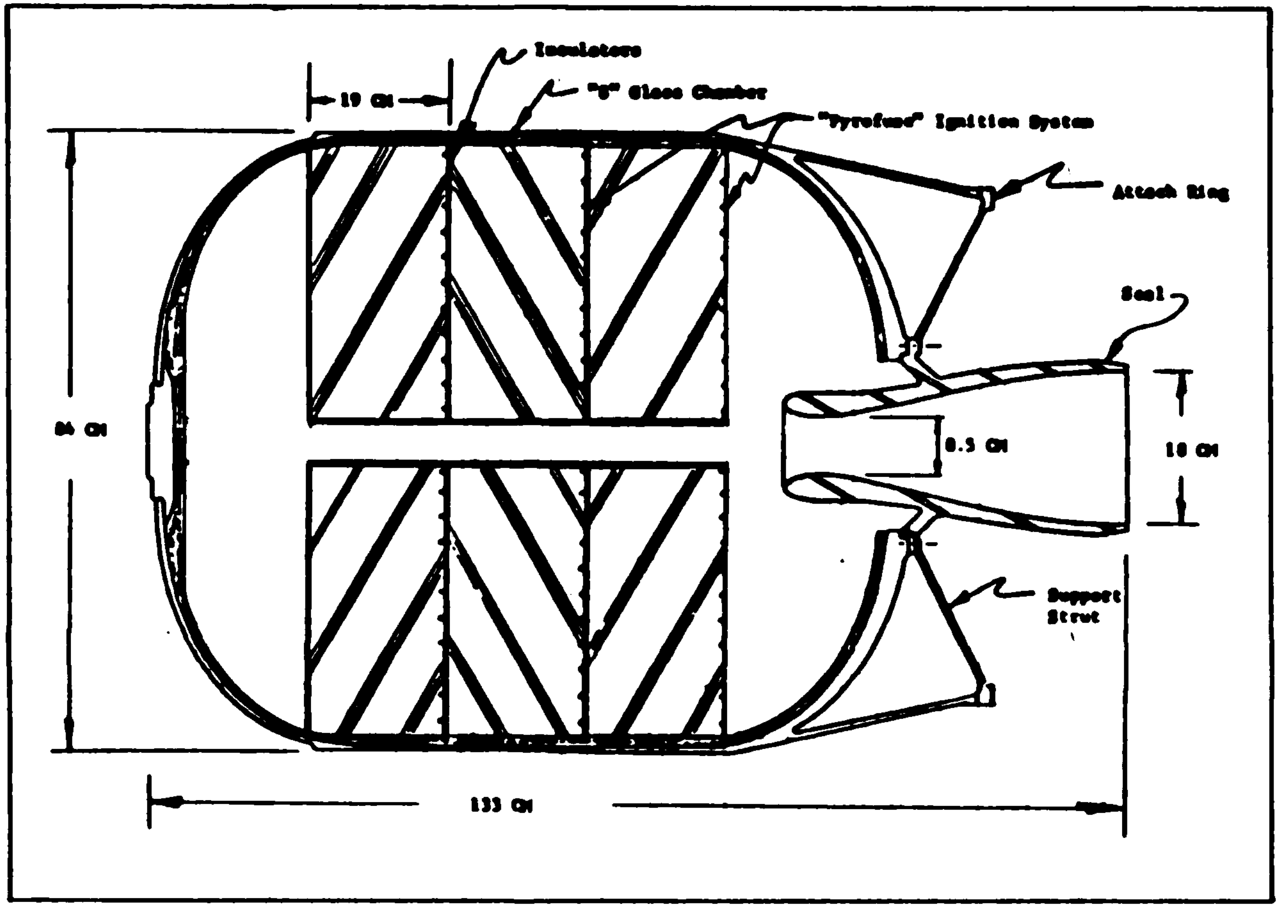

Fig. 14. Wafer Grain Solid Rocket Motor
Reprinted from (29:128)

bustion chamber at ignition (24:91). Since each layer has a larger open volume than the preceding layer, the ignitors will have to be larger or more potent for each succeeding layer. The time for such ignitors to fire is 5-15 milliseconds (24:92). Also, on each ignition the insulator layer which stopped the last pulse is ejected (29:117) and this needs to be designed to ensure it does not cause damage to the generator channel. Wafer grain motors with total burn times of 100 seconds and pulses as short as 1 second are possible (29:117). Loading efficiency, the amount of useable fuel per unit volume of the combustion chamber, increases with pulse length so that 4 second or longer pulses are more efficient (29:117).

The 100 second lifetime for a solid rocket motor mentioned previously is a restriction of the rocket throat. The throat area of any rocket engine has the greatest stress because of the high heat transfer (24:44). The lifetime may be longer for pulsed motors with sufficient time between pulses for radiative cooling, but more research is needed to determine how much longer. Active cooling can extend the throat lifetime but this is not usually done with solid rocket motors (24:47). Unlike liquid fueled engines, solid motors do not have liquid fuel or oxidizer to act as a coolant on its way to the combustion chamber. The use of the hybrid solid rocket motor would provide liquid for cooling and should be

explored if generator uses require longer lifetimes than can be provided by uncooled systems. For uncooled systems, an insert of pyrolytic graphite has proven to be the best material to resist the erosion which occurs at the throat (31:445). Even then, solid rockets cannot presently have continuous burn times longer than 120 seconds (5).

V. Generator Analysis

Fuel Parameters

The solid fuel considered suitable for this analysis is a double-base metalized fuel. Such a fuel has been used in previous MHD experiments (3:1647). Although the fuel is much the same as that used in rockets, MHD generators require the addition of some seeding material like potassium nitrate to increase electrical conductivity (2:2-4).

The operational mass flow rate of the gas is set at 30kg/sec. Although the wafer motor described in the previous chapter has a mass flow rate of 10kg/sec (29:129), this generator will have a larger volume. Since the 30kg/sec rate is in the middle of presently considered MHD design parameters (29:34), it is a conservative estimate.

The gas velocity in the channel is set at 2000m/sec. Past experiments with linear channels using solid fuel motors have produced exit gas velocities of 2260m/sec (3:1647). Disk generators have larger expansion ratios than linear generators, and so have larger exit velocities. In addition, exhausting to a vacuum would increase the exit velocity. A conservative approach, however, has been taken because modeling the flow characteristics of a disk channel are difficult.

Fuel density and burn rate, when combined with the mass flow rate, determine the volume and total mass of the

fuel. Fuel density for such fuels is about 2g/cm^3 (29:127) and typical burn rates are 1-2cm/sec (29:121). A 1m diameter cross section of fuel would produce a mass flow of 30kg/sec with a burn rate of 1.91cm/sec.

For a total burn time of 115 seconds, including the 15 seconds needed to charge the magnet, the wafer fuel cartridge would be 2.2m long, 1m in diameter, and have a mass of 3450kg. In previously built wafer motors, the mass of the fuel is about 85% of the total mass of the motor, including case, liner, ignitors, and nozzle (29:129). Using this scaling percentage, the total mass of the motor is about 4060kg. Motor length is set at 3m.

Channel Parameters

The dimensions of the disk channel are proportional to those of a previous disk generator experiment (13:8) but have been increased to accommodate a 1m diameter rocket motor. The final design (Fig. 15) includes a torus exhaust manifold, or diffuser, with ports around the outer edge of the channel. Aside from serving as a structure to control the exhaust of waste effluent, the diffuser also gives support to the disk channel without putting support structures through the channel itself (26:1509). In addition to the diffuser support, it may be necessary to stiffen the disk plates to avoid warping at operational pressures (13:71). Such requirements would be determined in tests.

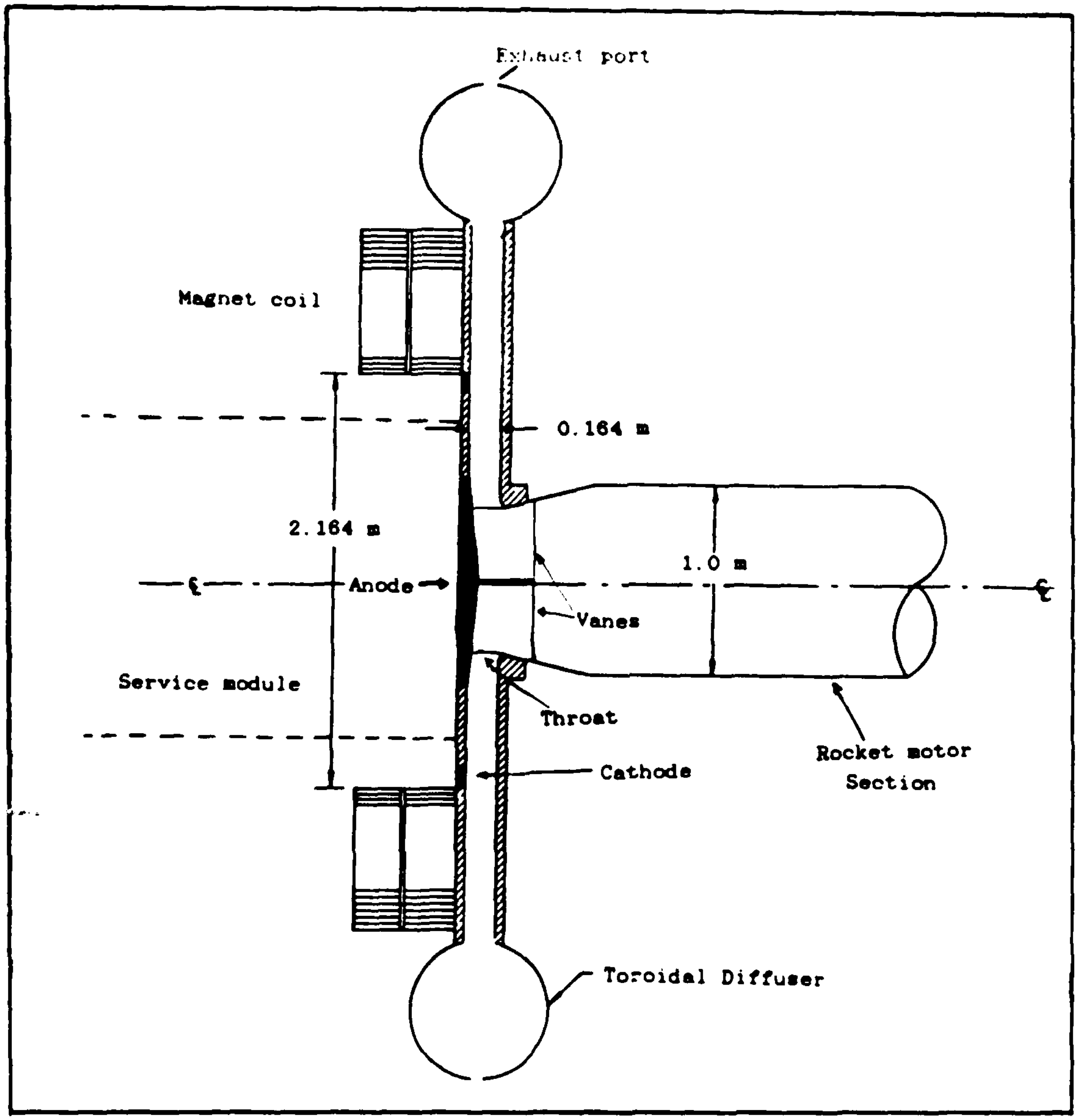

Fig. 15. Final Disk Generator Design
Adapted from (13:8)

A closer view of the swirl vanes is shown in Fig. 16. The actual number and curve of the vanes would have to be determined by testing. It should be noted, however, that the placement of the vanes before the throat is appropriate. Redirecting the gas flow, such as swirling, is easier when the gas is still subsonic (5). Therefore, the vanes should be before the Mach 1 transition at the throat.

Magnet Parameters

The overall diameter of the disk generator, including the diffuser, is dependent on the size of the magnet coil. The size of the coil is dependent on the size of the working channel volume and the desired field strength. The working volume is the inner diameter of the magnet, 2.164m, with the channel width of 0.164m. The desired field strength is 6 tesla.

A simple iterative method was developed to estimate the mass and cross section of the magnet coil. According to studies of similar coils used in disk generators, the weakest point of the magnetic field is at the center of the channel (13:17). Therefore, a conservative approach is to design a magnet that gives the desired field strength at this weak point.

The magnet was modeled as a simple current loop (Fig. 17) of radius, a, and current, I. The design point, P, is a distance, x, away from the center of the current loop on a line perpendicular to the loop . The measure of the

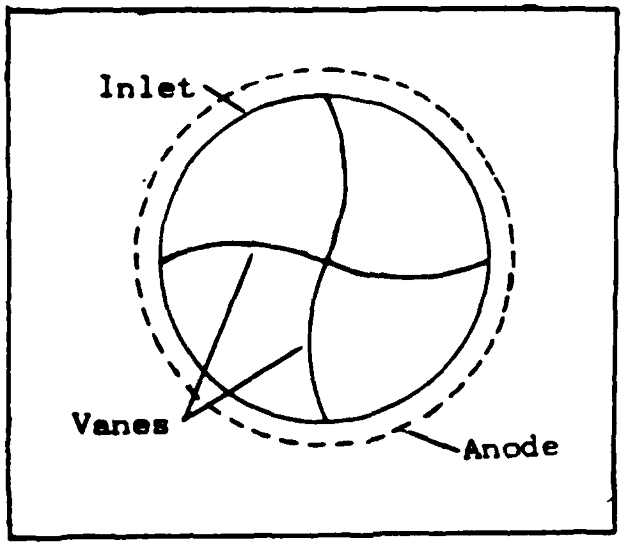

Fig. 16. Inlet View of Swirl Vanes

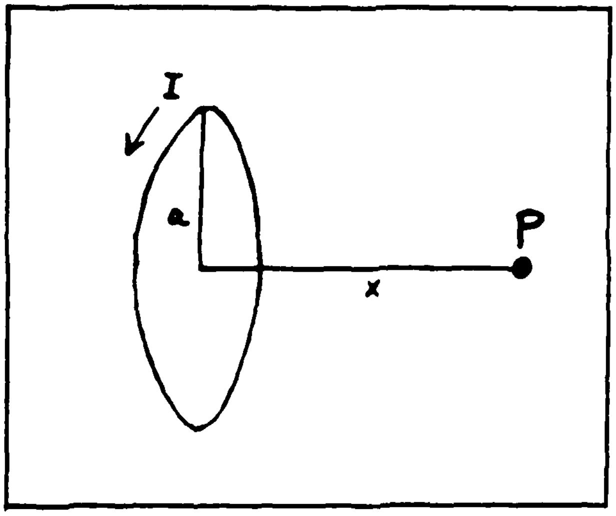

Fig. 17. Current Loop Estimation of MHD Magnet Adapted from (7:787)

magnetic field strength at P, B, is given by the following equation (7:787):

$$B = (\mu_0/2)[(Ia^2)/(x^2 + a^2)^{-3/2}] \qquad (6)$$

where

μ_0 = permeability constant

Since the desired field strength, B, is already known, the equation is solved to find the current, I. The first iteration puts the radius, a, at the inner radius of the proposed magnet, in this case 1.082m. The measure for x is the width of the channel, 0.164m. After calculating the value for I, the necessary cross section for such a current is calculated using the design current density. In the previous chapter, that current density was set at 15,000A/cm². This cross section is used to adjust the value for a. The new radius now goes to the center of the cross section. The inner radius of the magnet remains the same. The new radius is substituted for a in the current calculation and a new current is found. This process continues until the change in a is less than 1%.

The calculated cross section and the inner diameter of the magnet are used to find the volume and mass of the magnet coil. The mass density of the coil is close to that of copper, so the density of copper (8.9g/cm³) is used (27:125). The resulting cross section is 0.08m² with a mass on the order of 5500kg.

Estimating the additional mass of shielding and the cooling system is difficult. The cooling system is primarily liquid helium which is stored in a tank until the magnet is readied for use. Although one filling of the magnetic dewar should last well past the total burn time, this coolant would have to be replenished periodically. A conservative estimate is increasing the conductor mass by a factor of 2. Therefore, the estimated mass of the magnetic subsystem is 11,000kg. The power required by such a magnet subsystem is on the order of a few megawatts (13:4).

The addition of the magnet cross section into the disk design would set the diameter of the generator on the order of 4m, assuming a 0.5m diameter cross section for the diffusion torus. This is in accord with the cargo space available in the space shuttle (37:90,288). A good estimation rule to find the system dry mass for a linear MHD system is the mass of the magnet, which is usually 60-70% of the system mass (29:26). The magnet system is smaller in a disk generator, so a conservative estimate is to double the magnet system mass for an estimated dry mass of 22,000kg. The addition of the fuel would bring the estimated mass of the system to 25,450kg. This mass is within the design constraints of the space shuttle but over its demonstrated capabilities (37:102). Since the disk section can go up in one piece, it should be possible to send up the power conditioning subsystem or the combustor

subsystem in a separate trip if the shuttle could not take the entire generator.

Power Parameters

To calculate the power output of any MHD generator, the electric field induced in the generator must be determined. The electric field in a Hall generator is related to a parameter, K, known as the load factor by the following equation (27:62):

$$K = | E(r)/(bvB) | \tag{7}$$

where

- $E(r)$ = the electric field in the radial direction
- b = the Hall parameter
- v = the radial velocity of the gas
- B = the magnetic field strength

For the maximum electrical efficiency, the load factor for a given Hall parameter is given by the following (27:63):

$$K = [(1 + b^2)^{1/2} - 1]/b^2 \tag{8}$$

Although one would like the Hall parameter in a Hall generator to be as high as possible, a reasonable value is 3 (29:34). Using the established magnet strength of 6 tesla and the gas velocity of 2000m/sec, the electric field is 8.6kV/m. Such a field can easily be supported by a disk geometry (26:1507).

Since the electric field is supportable, the load factor, K, can now be used to find the power density, P. For a Hall generator, the power density is determined by the following equation (27:63):

$$P = [b^2/(1+b^2)]K(1-K)\sigma v^2 B^2 \qquad (9)$$

The calculated power density for the disk generator is 709.68MW/m³. The working volume is set between the 1m diameter anode and the cathode ring with an inner diameter of 2m. Therefore, the theoretical power output from this disk generator design is 1346MW.

This is a much higher power output than the 300MW desired. If a decreased power level is needed, one method would be to reduce the mass flow rate of the fuel. In equation (1), the conductivity is roughly proportional to the mass flow rate. Decreasing the mass flow rate by half should decrease the conductivity by half, as well as the mass of the fuel carried. Such a reduction would still give an estimated power output of 673MW. A summary of the results is given in Table I.

System Comparison

As stated in the introduction, the MHD generator has been investigated as an alternative to nuclear and solar cell power systems. For solar cells, an array to produce 300MW would be almost 1.5km on a side (15:120). Such an array would be too ungainly for use in earth orbit.

TABLE I

Summary of MHD Disk Generator Design Estimates

Mass flow rate (kg/s)	Total fuel mass (kg)	Conductivity (mho/m)	Power out (MW)
10	1150	10	449
15	1725	15	673
20	2300	20	897
25	2875	25	1122
30	3450	30	1346

CONSTANT PARAMETERS

B-field (tesla)	Hall parameter	Burn time (s)
6	3	115

The most advanced nuclear system for space use is the SP-100 program. Although not yet operational, the system design calls for a power output of 100kW with a system mass of 3000kg or less (21:64). This would give a mass-to-power out ratio of 30kg/kW. The disk generator has a mass-to-power out ratio of 0.019kg/kW, an improvement by more than a factor of 1000.

There are two drawbacks to the disk MHD system described here. The first is that fuel has to be replaced after the 115 seconds of total burn time. It is envisioned that the fuel section and throat would disconnect from the generator to be replaced by a refurbished section. Replacing the fuel and the throat insert could then take place in the space shuttle bay or at the space station. Also, the magnet's supply of liquid helium would have to be replenished. These restrictions would have to be taken into account when evaluating a potential mission for the generator.

The second problem is the effluent from the exhaust. Optical sensors and lasers may be sensitive effluent jettisoned from the generator. It is possible to direct the exhaust into opposing jets that are perpendicular to the plane of the orbit and parallel to the earth. Such gas jets would put the particles into orbits that would not descend to cross in front of the sensitive equipment. Effluent effects is an issue for any future application.

VI. Conclusion and Recommendations

From the preliminary investigation done, the use of a rocket powered MHD generator does hold promise to fulfill future needs for high, pulsed electric power. The use of a disk channel coupled with a solid rocket motor offers simplicity and compactness and the advantage of thrust deflection. It must be noted, however, that the power and system mass calculations are extrapolated from past ground experiments and cannot be considered the exact performance parameters for a space system. Nevertheless, the factor of 1000 improvement in generator mass-to-power out over the present space power systems makes the rocket powered MHD generator a viable candidate for space missions requiring high, pulse power.

The MHD generator used in an open cycle does present the problem of refueling, and this would have to be considered for any prospective mission. The refueling would have to include replacing coolant for the superconducting magnet and refurbishing the throat insert as well as the solid fuel. In addition, the effluent would have to be directed away from sensitive instruments or have the generator separated from them, possibly by a tether. It is recommended that further research be conducted into the use of disk channel MHD generators using solid rocket motors and how they may be adapted for space use. The

research should include the following:

1. Development and testing of superconducting magnets for use in space

2. Improvement of throat inserts for solid rocket motors to extend lifetime

3. Investigation of effluent from rocket engines in space

In addition, as future power needs become clear, the suitability of the MHD generator should be reassessed.

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Magnetohydrodynamic generators
Spacecraft power systems

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Title: INVESTIGATION OF ROCKET POWERED, OPEN CYCLE, MAGNETOHYDRODYNAMIC GENERATORS FOR HIGH, PULSED POWER NEEDS IN SPACE

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Block 19

This investigation examined the possibility of using a rocket powered magnetohydrodynamic ~~(MHD)~~ generator for pulse power in space of 300 megawatts (MW). The result is a preliminary design of an MHD generator using an open cycle disk channel and a single superconducting solenoid coil. The disk channel acts as a thrust deflector, and internal vanes counteract induced vorticity. The use of a solid fuel, wafer grain design rocket motor is proposed for increased electrical conductivity and pulse operation of the generator. Using conservative parameters, a generator design capable of being carried on one or two space shuttle launches is developed with estimated mass of 24,450kg and estimated power output of 1346MW. The nominal operation time before refurbishment is 115 seconds; the restriction on operation time is deterioration of the channel throat. This design exceeds present nuclear and solar cell power systems in power output per unit mass. (Theses)

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